

Thermal safety analysis of aluminum matrix B₄C irradiation in-pile

MI Xiangmiao QIAN Dazhi ZHANG Zhihua HUANG Hongwen GUO Haibin

Institute of Nuclear Physics and Chemistry, China Academy of Engineering Physics, Mianyang 621900, China

Abstract Aluminum matrix B₄C is a new structural material for spent fuel storage and related performances need in-depth research, especially the irradiation-resistance capability. The thermal calculations were completed by using the CFD software to ensure the safety of the in-pile irradiation test. Considering the characteristic of the irradiation project, the thermal safety feature of the in-pile test was analyzed, and the irradiation project was optimized.

Key words Aluminum matrix B₄C, Irradiation in-pile, Thermal, Safety analysis

1 Introduction

B₄C is a special nonmetal material and its application in nuclear physics, microelectronics, space technology and other fields spreads more and more widely. With wide energy spectrum and big section for neutron capture, B₄C has strong performance in neutron absorption, only behind gadolinium, samarium, cadmium and few elements. Meanwhile, low price, strong corrosion resisting and good thermal stability make B₄C more and more important in nuclear reactor materials. “B₄C pellet for nuclear industry” is enrolled into the State 863 projects during the period of the 15th national conference. Now the application of B₄C in nuclear reactors focuses on the radiation shield, the reactor control rod and preventing the leak of radioactive materials^[1].

As a new structural material for spent fuel storage, Aluminum matrix B₄C has many advantages, such as economical efficiency, strong neutron absorption ability and excellent mechanical behavior. We conduct the in-pile irradiation of samples to test the material's irradiation resistance performance and the thermal safety analysis is done to ensure that the irradiation test is safe. The work uses the CFD software, Fluent, gives out thermal hydraulic parameters of irradiation device, such as the flow distribution, heat transfer characteristic and temperature field^[2].

2 Samples and irradiation device

Aluminum matrix B₄C is a mixture of B₄C dust and aluminum powder, through pressing, sintering, squeezing, hot rolling and other procedures. The irradiation specimens are machined into two sizes, tensile and rectangular, according to the demand of manufacture assignment book, GB/T228-2002, GB/T230-2002, and also convenient for in-pile irradiation and performance test after the experiment. The shapes are showed in Fig.1. To compare irradiation properties of samples with different B₄C content, three kinds of specimens are made, 10%, 25% and 31%.

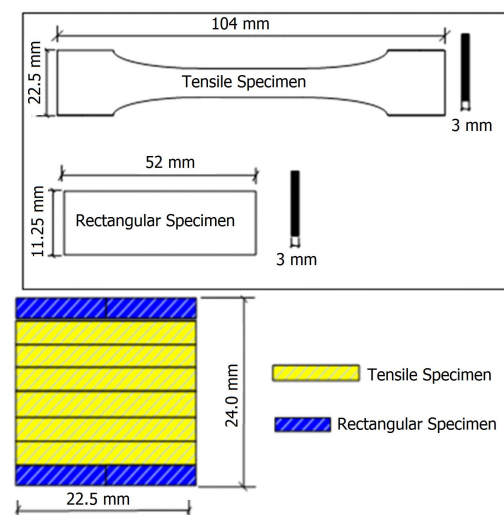


Fig.1 Irradiation specimens (a) and samples (b) of Aluminum matrix B₄C.

* Corresponding author. E-mail address: mxm04@126.com

Received date: 2012-12-31

Irradiation samples are assembled with the two specimens, placed in the irradiation box. The gaps and contact resistance between specimens are neglected to model and compute easily, so the samples are rectangular solids in the computation model. The irradiation box is with no cover on the top, holes in the bottom and aluminum cross are put under the sample to avoid blocking the holes. The aluminum matrix B₄C irradiation test technically requires that the irradiation is going with γ , fast neutrons and no thermal neutrons, so the irradiation box is covered by cadmium skin outside and Al skin inside. The structure of irradiation boxes is showed in Fig.2.

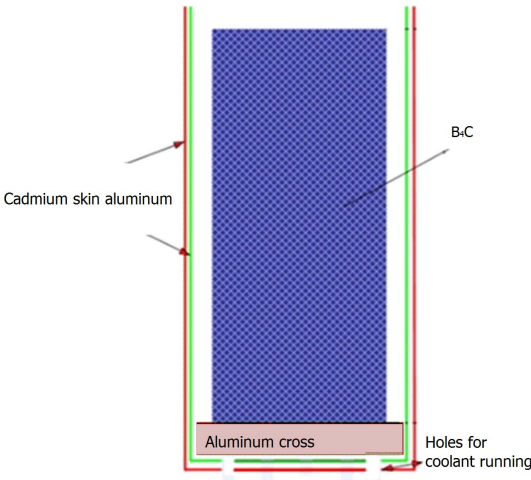


Fig.2 Structure picture of irradiation box.

The shape of irradiation device and aluminum block in the irradiation channel is similar. Four irradiation boxes are put in the device, fixed with an aluminum block (hollow sticks) in either end or ribs around. An aluminum cross and cadmium plate are placed in the bottom of the top aluminum block, and the width of the cross is smaller than the hole diameter. The bottom aluminum block is slotted in both ends.

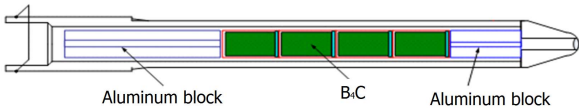


Fig.3 Scheme of irradiation device.

The outer channel between irradiation box and irradiation device is to cool the cadmium skin, and the inner channel between irradiation box and samples is to cool the samples. Fig.4 shows the cross section of the irradiation device.

3 Heat power of samples

The heat power of samples and cadmium skin, calculated out with MCNP, under full reactor power is listed in Table 1.

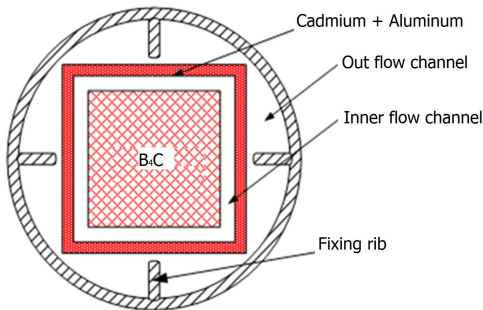


Fig.4 Structural sketch of sample's cross-section.

Table 1 Heat power of irradiation samples and cadmium shell with full reactor power

Irradiation box	Heat power / W·cm ⁻³		
	Samples	Cd skin around	Cd skin at the bottom
First	9.73	155.33	134.74
Second	12.02	197.70	163.85
Third	14.13	227.02	194.49
Fourth	13.71	224.46	400.81

Being small, the heat power's change of each sample in the axial direction is ignored. The aluminum material gives out little heat, 3.38 W/cm³.

4 Thermal analyses

So complicated the computational model is, that two simplifications are made: The influence of the topmost handle is out of thought. The ribs fixing the irradiation boxes are ignored. The other structural details of the irradiation device are totally considered, including holes at the irradiation boxes' bottom, outer cadmium skin, aluminum crosses, tank in aluminum blocks.

This computation adopts *k-ε* two-equation turbulence model, and sets the pressure loss between inlet and outlet equivalent to standard fuel rods. The coolant's thermodynamic parameters are set as values at the inlet of reactor core with full power. The roughness height of walls is 0.0016 mm, equal to cold drawn tubes^[3].

Make a plane of symmetry by cutting the model with the diagonal line along the axis, and the

temperature distribution is showed in Fig.5. Though with high heat power, Cadmium skin's temperature approximates to irradiation samples at the same depth due to small thickness and located between inner and outer flow channel. The temperature of the plane of symmetry gradually increases, to the highest, 59°C, at the bottom of the fourth box.

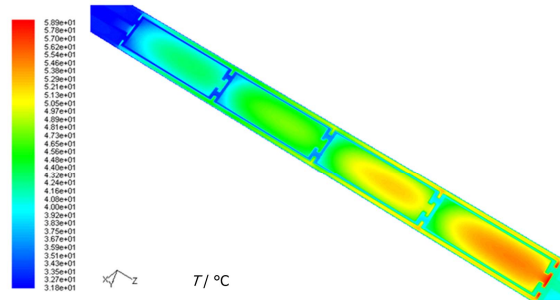


Fig.5 Temperature distribution of irradiation device's symmetry face.

The temperature curve on the irradiation device's centre axes is presented in Fig.7. The temperature starts fast rising from the 0.42 m position (the first box's top), after that four wave crests stand, higher one by one and representing the four boxes' temperature change tendency. The first maximum appears at the three fifth height of the box, and then the temperature drops rapidly due to heat transfer from the bottom of the box to the coolant. Between two peaks there are some temperature points lower than nearby, referring to the structure of the irradiation box, which means the coolant's temperature. That is because the box is not filled totally, some space remaining at the top and filled by the coolant. The temperature changing tendency of each box is similar, and the cadmium skin at the fourth box gives out more heat, bringing the temperature rise. On the centre axis, the coolant channel follows the four boxes, so the temperature curve takes a leap down after the four wave peaks.

The cross section of cadmium skin is a square ring. Make a temperature profile with values on the centre axis of each side. From Fig.6 and Fig.7, we can see that the cadmium temperature's change tendency is similar to samples at the same height, the former slightly lower than the latter.

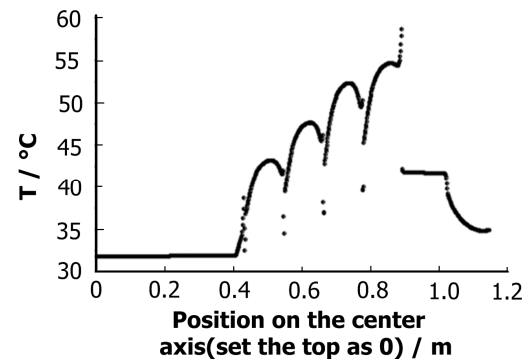


Fig.6 Temperature curve of irradiation device in axial direction.

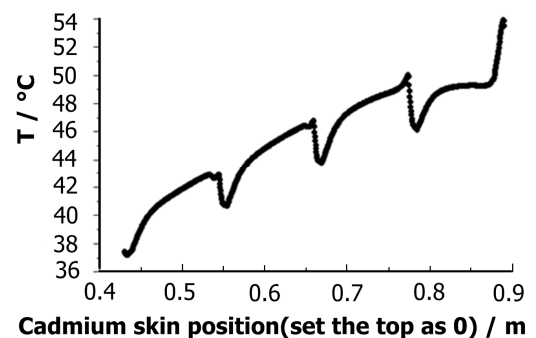


Fig.7 Temperature curve of Cd shell in axial direction.

In Fig.6 the samples' centre temperature reaches the maximum at 850 mm, whose temperature distribution is showed in Fig.8.

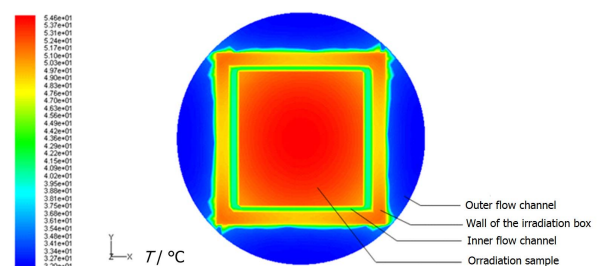


Fig.8 Temperature distribution of irradiation device cross-section at 850 mm position.

There is no rib in the irradiation box to fix the samples in the radial direction therefore it's highly possible that samples act the box wall. In addition, the samples probably swell during the irradiation reducing the cooling ability. The two cases will worsen the heat transfer, so it's necessary to consider these conditions

in calculation^[4]. With the existing results and simplified models, the results are presented in Fig.9.

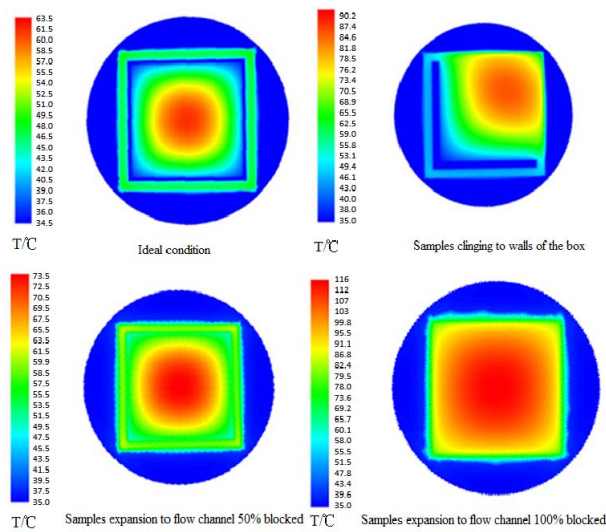


Fig.9 Temperature distribution sketch of irradiation device cross-section with different conditions.

The temperature of cadmium skin in simplified model with ideal conditions, 10°C below samples, is a little lower than the full-scale model, but the sample's temperature does not have profound change. So the simplified model is believable. The simplified model's highest temperatures with ideal conditions, samples clinging to box walls, samples expansion to flow channel 50% blocked, samples expansion to flow channel 100% blocked are 61°C, 90°C, 74°C and 117°C. The request of test design says that the samples' temperature should be under 400°C and cadmium under 200°C, so there is relatively large space to the safe threshold value.

5 Conclusion

The highest temperatures of cadmium and irradiation samples in full-scale model with ideal conditions are 52°C and 60°C. The highest temperature of samples, 117°C, in the simplified model with flow channel totally blocked is still under limit value. In actual situation, these things will have influence on the heat transfer.

In full-scale model the ribs fixing the irradiation boxes are not considered, and they will decrease the outer channel flow, reducing the coolant.

Thermal contact resistant is neglected, but this simplification affects little according to experience.

The heat power of sample is handled with the uniform distribution, a little difference occurs from the actual situation.

Aluminum matrix B₄C is a new structural material for spent fuel storage, and in-pile test would push forward the research. The simulation results present that the irradiation test is safe, reliable, and provide theoretic guarantee for next work.

References

- 1 Cao Z W, Zhang J H. Adv Mater Industry, 2006, **5**: 59–61.
- 2 Tao W Q. Numerical heat transfer. Xi'an: Xi'an Jiaotong University Press, 2001, 508–509.
- 3 Li B S. Some problems in engineering heat transfer. Beijing: Atomic Energy Press, 2008, 149–152.
- 4 Han Z Z, Wang J, Lan X P. Fluent-fluid engineering simulation examples and application. Beijing: Beijing Institute of Technology Press, 2010, 128–135.